

REPORT No. 551

AIRCRAFT COMPASS CHARACTERISTICS

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SUMMARY

A description of the test methods used at the National Bureau of Standards for determining the characteristics of aircraft compasses is given. The methods described are particularly applicable to compasses in which mineral oil is used as the damping liquid. Data on the viscosity and density of certain mineral oils used in United States Navy aircraft compasses are presented. Characteristics of Navy aircraft compasses IV to IX and some other compasses are shown for the range of temperatures experienced in flight.

Results of flight tests are presented. These results indicate that the characteristic most desired in a steering compass is a short period and, in a checking compass, a low overswing.

INTRODUCTION

Liquid-damped compasses have been extensively used in the navigation of surface ships, but it was not until their use in faster maneuvering aircraft that the dynamic characteristics of the card became of foremost importance. Numerous attempts have been made to analyze the motion of the liquid-damped compass card (references 1, 2, 3, 4, and 5), on the assumption that such an analysis would aid in the evaluation of the characteristics that a compass to be used in a specified manner should have. These attempts have yielded only approximate solutions, which have not aided the authors materially in clarifying the problem of the selection of suitable compass characteristics.

The data presented herein were obtained at the request, and with the financial support, of the Bureau of Aeronautics, Navy Department. The National Advisory Committee for Aeronautics furnished the financial support essential for the preparation of the report. The authors wish to acknowledge the close cooperation of W. G. Brombacher, National Bureau of Standards, C. L. Seward, Bureau of Aeronautics, Navy Department, and Ira E. Hobbs, lieutenant, United States Navy.

MOTION OF LIQUID-DAMPED COMPASS CARDS

The effect of the liquid that is carried around by the card is as if there were another disk of varying moment of inertia connected to the magnetic card by viscous

friction of varying magnitude. The complicated nature of the motion is indicated by the data presented in figure 1, which shows the motion of a Navy IX aircraft compass card after release from rest at a deflection of 30° (solid line) and after release from rest at a deflection of 10.5° (dotted line). The decrement in successive amplitudes of the first motion is far from constant, an observation not in agreement with the usual simplified theories. Although the card comes to rest at the end of the first overswing of 10.5° , the liquid continues in motion and reduces the second overswing, so that the ratio $10.5:2=5.25$ of second to third amplitude is much greater than the ratio $30:10.5=2.86$ of first to second amplitude. If the card is held steady at a deflection of 10.5° until the liquid has had time to come to rest and then released, the overswing is 3.7° and the ratio is $10.5:3.7=2.84$.

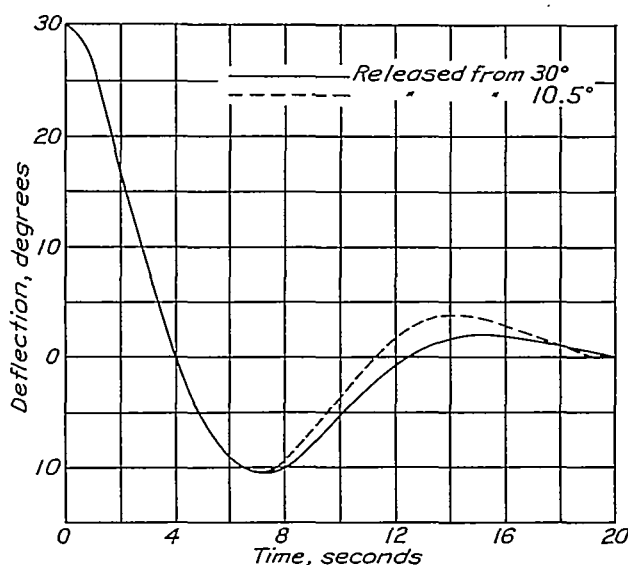


FIGURE 1.—Time-deflection curves for United States Navy IX liquid-damped aircraft compass at a temperature of 20°C .

In order to produce the motion indicated in figure 1, only the compass card was deflected, the case remaining stationary. In actual use both the compass card and the case are moving and there will be an additional effect on the motion of the card owing to the motion of the case from which it is separated by a relatively narrow layer of liquid. The authors have reached the

conclusion that a satisfactory analysis of the motion of the card including all of the factors involved would be extremely complicated.

OPERATING CHARACTERISTICS

In the absence of a satisfactory theory, the relation between operating characteristics that can be measured in the laboratory and behavior in flight must be determined empirically. For practical convenience, the operating characteristics of a compass are defined by three constants, which can easily be measured in the laboratory as described below. These constants are:

(1) The time of swing 30° to 5° , which is closely related to the period of the compass.

(2) The overswing from 30° , which depends principally upon the relative values of the moment of inertia and magnetic moment of the card and the viscosity of the damping liquid.

(3) The swirl, which serves as a measure of the effect of motion of the case on the motion of the card.

Following is a detailed description of the methods used at the National Bureau of Standards for determining these characteristics.

Time 30° to 5° .—The card is magnetically deflected 30° from its equilibrium position, held at this position long enough for the liquid to come to rest, released, and the time observed for it to pass through an angle of 25° toward its equilibrium position. The same test is repeated, deflecting the card 30° in the opposite direction. The position of the compass should not be changed between the two tests. The average of the observed times is defined as the "time 30° to 5° ." The purpose of making observations for deflections in both directions is to average out any error due to incorrect setting of the lubber line with reference to the equilibrium position of the card.

Overswing.—The card is magnetically deflected 30° from its equilibrium position, held at this position long enough for the liquid to come to rest, released, and the overswing past the equilibrium position noted. The test is repeated, deflecting the card in the opposite direction. The position of the compass should not be changed between the two tests. The average of the two observations is defined as the "overswing." In practice it is convenient to combine the test for the time 30° to 5° and for the overswing.

Swirl.—The compass is mounted on a motor-driven turntable, and turned through an angle of 90° at a rate of 30° per second. During the turn, a swirling motion is transmitted to the damping liquid, and some of this motion is transmitted to the card. The maximum deflection of the card from its true position, which occurs after the turn has been completed, is noted and defined as the "swirl."

These three operating characteristics are affected in the first order of magnitude by two variable factors, (1) the temperature and (2) the horizontal magnetic

field strength. It has been determined by experiment that temperature affects only the viscosity and density of the damping liquid. Temperature has a negligible effect on the magnetic moment of the permanent magnets. The International Critical Tables give 0.0002 per degree centigrade as the temperature coefficient of magnetic moment of cobalt magnet steel. This amounts to a change of 1 percent for a 50° C. change in temperature. The magnetic moment increases as the temperature is decreased. Variation of the operating characteristics with viscosity of the damping liquid is both more conveniently and more accurately determined by filling the compass with mineral oil having the required viscosity at room temperature than by changing the temperature of the compass. It is not necessary to make a separate determination of the effect of density, since the density of the liquids used can be expressed as a function of the viscosity alone.

DAMPING LIQUIDS

The method developed by Cragoe (reference 6) for representing changes in viscosity of liquids with changes in temperature and composition has been used. The reader is referred to Cragoe's article for full details of the method, but a short description will be given here. Cragoe has found that, to a very good approximation, a certain function of absolute viscosity (or of kinematic viscosity) for which the name "liquidity" has been suggested, is linearly related to temperature, that its reciprocal is linearly related to pressure, and that a linear mixture rule is applicable to such a function.

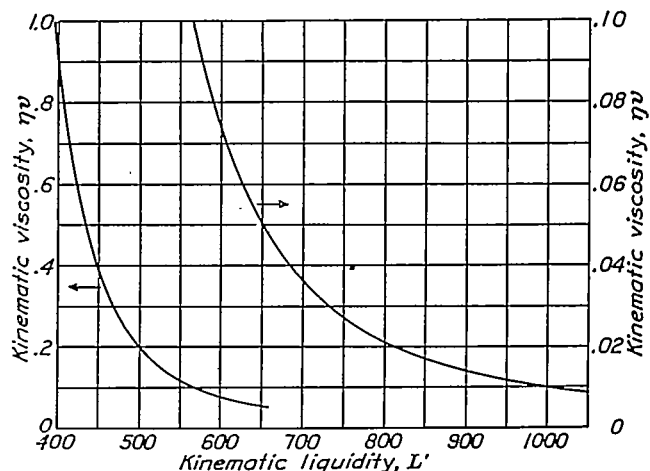


FIGURE 2.—Cragoe's kinematic liquidity as a function of kinematic viscosity.

Designating the liquidity by L when it refers to absolute viscosity and by L' when it refers to kinematic viscosity, it is defined by the equations

$$\eta = Ae^{B/L}$$

$$\eta v = Ae^{B/L'}$$

where η is the absolute viscosity, and v is the specific volume, both in cgs units; A and B are the same constants in the two equations. The numerical value of A is 5×10^{-4} and that of B is $1000 \log_e 20$.

Figure 2 shows the relation between the kinematic liquidity L' , and the kinematic viscosity ηv . The relation between kinematic liquidity and temperature for some representative compass liquids is shown in figure 3.

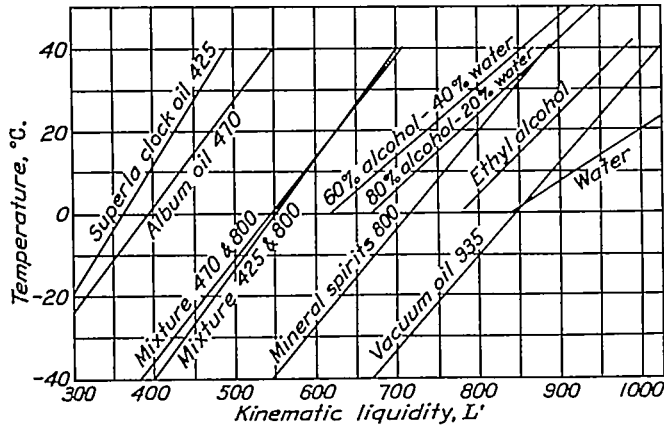


FIGURE 3.—Temperature-liquidity curves for compass damping liquids.

It has been found that Cragoe's equation for mixtures is directly applicable to mixtures of mineral oils used as compass damping liquids.

$$L'm = xL'_1 + (1-x)L'_2$$

$L'm$ = the kinematic liquidity of the mixture.

L'_1 and L'_2 = the kinematic liquities of the component liquids.

x = the fraction by weight of component No. 1.

The rule does not, however, apply to mixtures of alcohol and water as will be seen by reference to the curves for these liquids in figure 3. The viscosity data on alcohol and water have been taken from Bingham and Jackson (reference 7).

Figure 4 shows that except for the alcohol-water mixtures, which also showed an anomalous behavior in figure 3, the density is a single-valued function of the liquidity for all the liquids considered. In other words, the density of the damping liquid varies with the liquidity, independent of the particular mineral oil used. For example, if the liquidity of vacuum oil at -15°C ., is equal to the liquidity of mineral spirits at 15°C ., the densities are also approximately equal.

The data at 16°C . shown in figure 4 were obtained by actual measurement of the density and liquidity of damping liquids. The densities at -15°C . and 40°C . were extrapolated on the basis of the value at 16°C .

from the National Standard Petroleum Oil Tables (reference 8). The liquities for these temperatures were obtained from figure 3.

EFFECT OF TEMPERATURE AND LIQUIDITY

The variation in the characteristics of some representative compasses with temperature and liquidity of the damping fluid are shown in figures 5 to 21. The characteristics of time, overswing, and swirl are plotted against liquidity. The temperature-liquidity

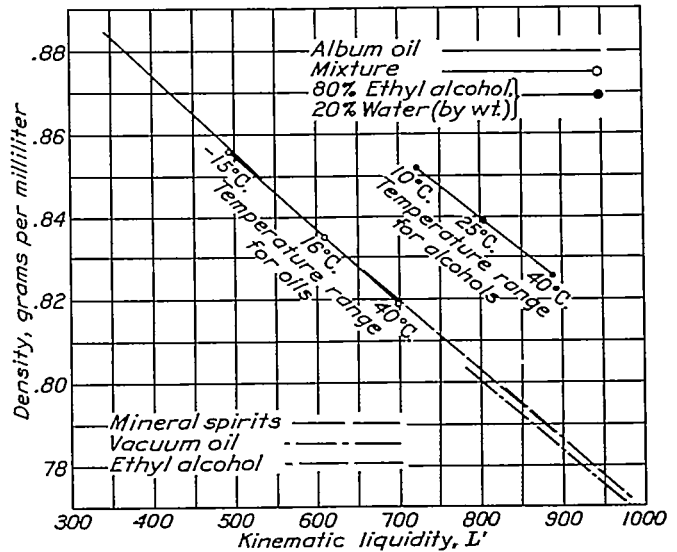


FIGURE 4.—Density liquidity curves for compass damping liquids.

relations for several liquids are shown by the several straight lines. To determine the characteristics of a compass at a given temperature, enter the chart at the temperature value on the right-hand scale, determine the liquidity for the liquid being used, and read the characteristics corresponding to this liquidity. The liquidity lines for the liquids commonly used in the compass are shown as solid lines.

The characteristics were usually determined for one compass, picked as representative of the type. When possible, five compasses were tested at room temperature with the original liquid and, on the basis of the data thus obtained, the average compass of the five was selected for complete tests. Another compass of the same type might have slightly different characteristics. The observed points are indicated on the curve sheets and the best smooth curves are drawn through the points.

Some specifications regarding the details of the compasses tested are given in table I. The values omitted were not available to the authors.

The Navy Department now uses or in the past has used as damping liquids, mineral oils of four different

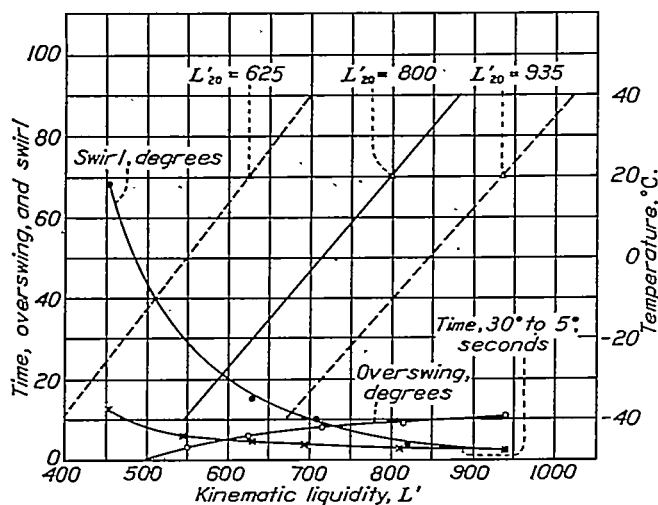


FIGURE 5.—Characteristics of United States Navy NSH aircraft compass.

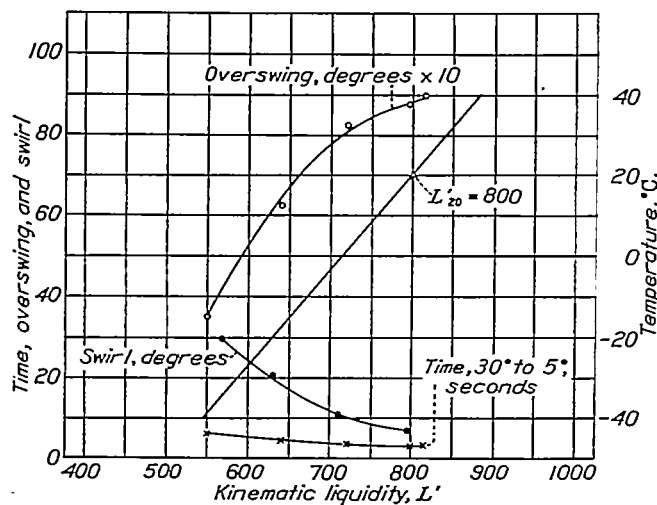


FIGURE 6.—Characteristics of United States Navy IV aircraft compass.

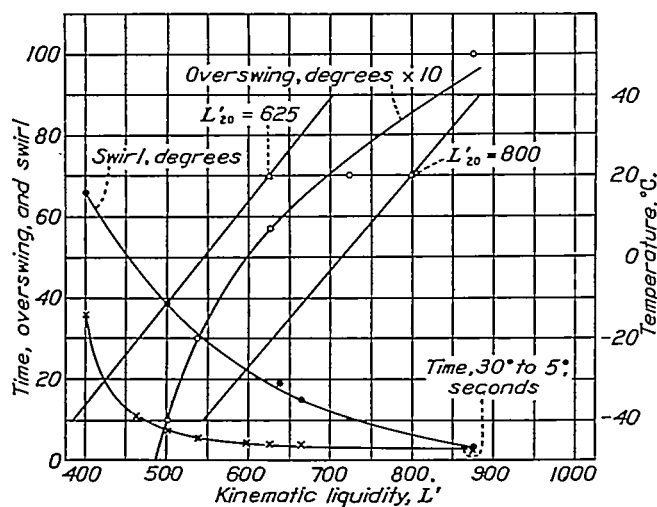


FIGURE 7.—Characteristics of United States Navy V and VA aircraft compasses.

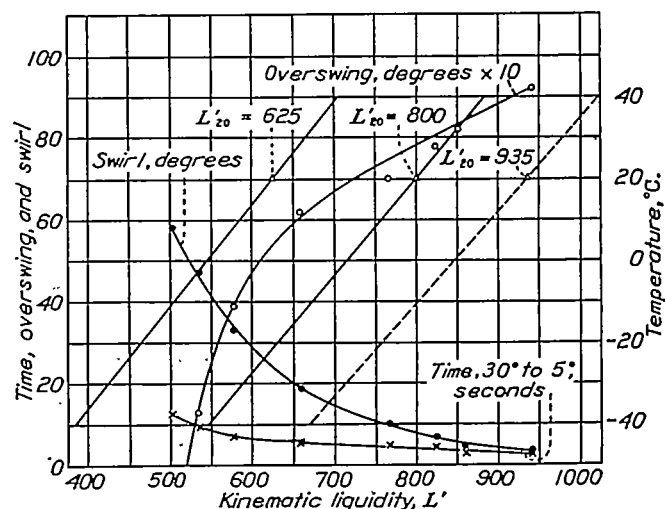


FIGURE 8.—Characteristics of United States Navy VB and VO aircraft compasses.

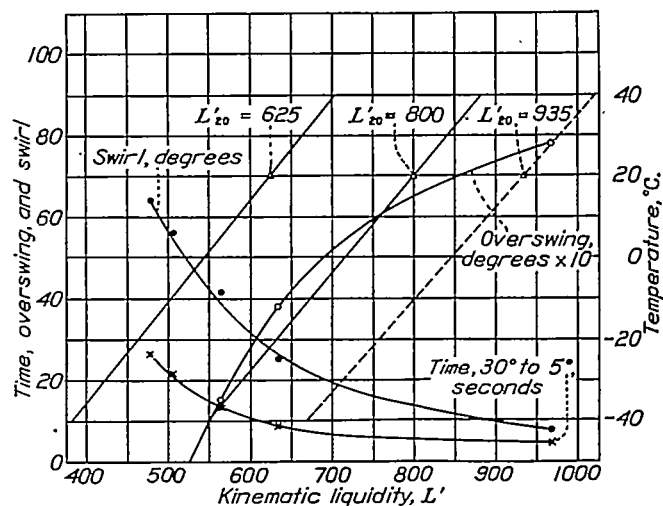


FIGURE 9.—Characteristics of United States Navy VI and VIA aircraft compasses.

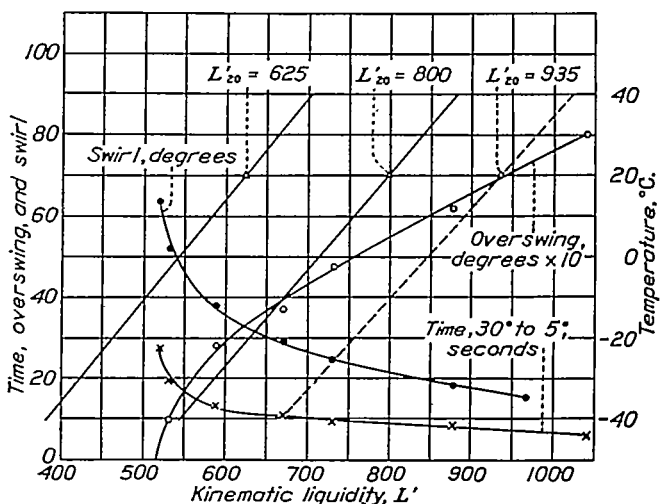


FIGURE 10.—Characteristics of United States Navy VIB aircraft compass.

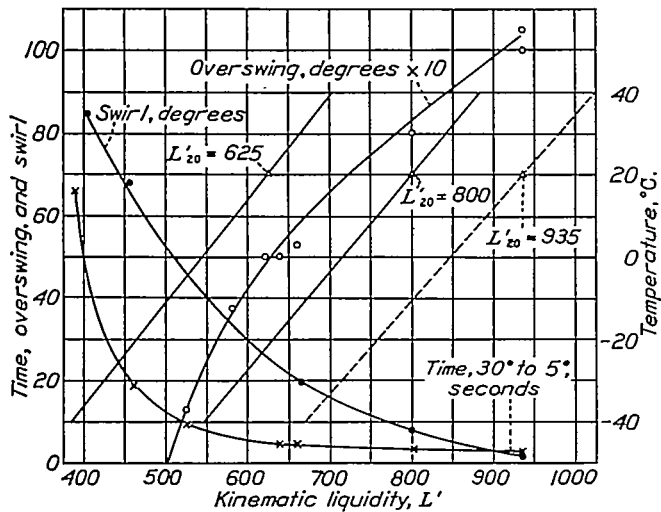


FIGURE 11.—Characteristics of United States Navy VII and VIIA aircraft compasses.

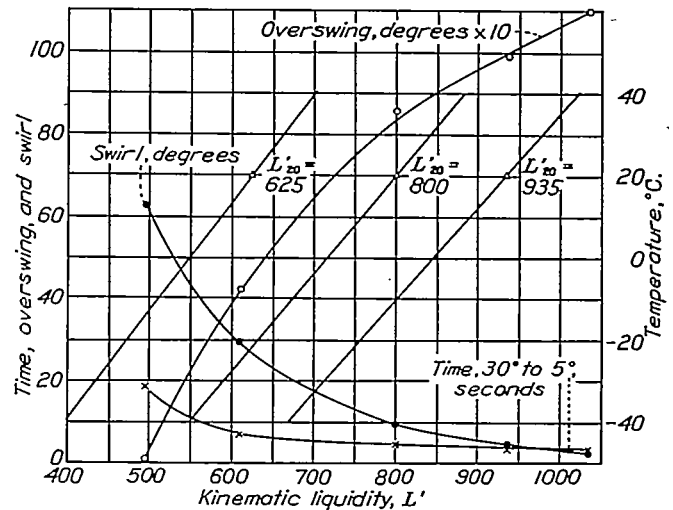


FIGURE 14.—Characteristics of United States Navy IX aircraft compass.

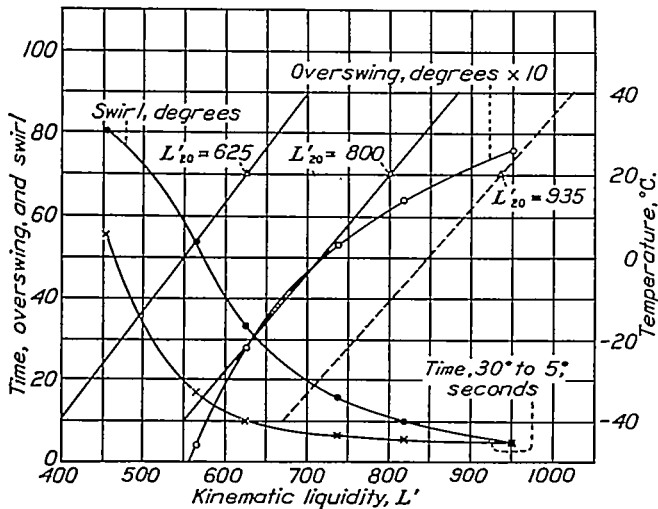


FIGURE 12.—Characteristics of United States Navy VIIIB aircraft compass.

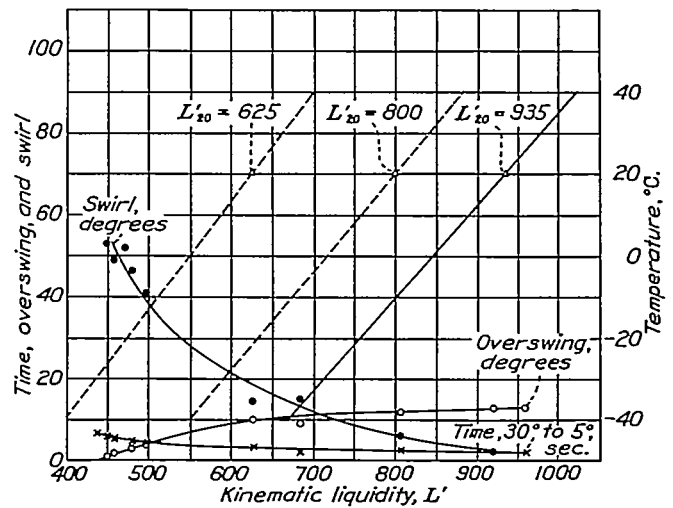


FIGURE 15.—Characteristics of United States Army B3 aircraft compass.

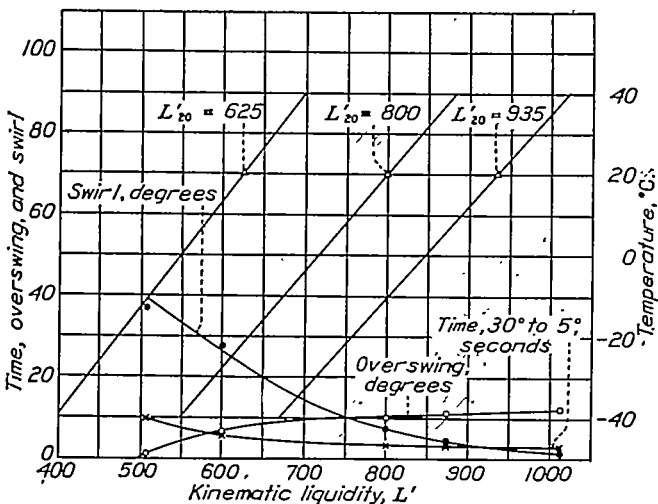


FIGURE 13.—Characteristics of United States Navy VIII aircraft compass.

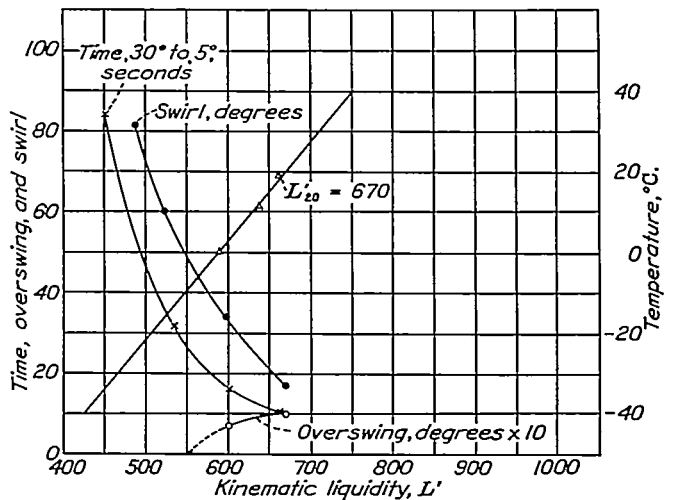


FIGURE 16.—Characteristics of United States Army D4 aircraft compass.

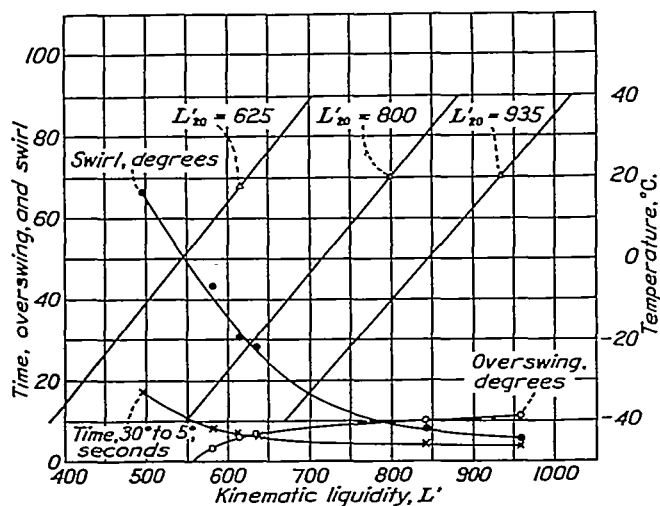


FIGURE 17.—Characteristics of KT58 aircraft compass.

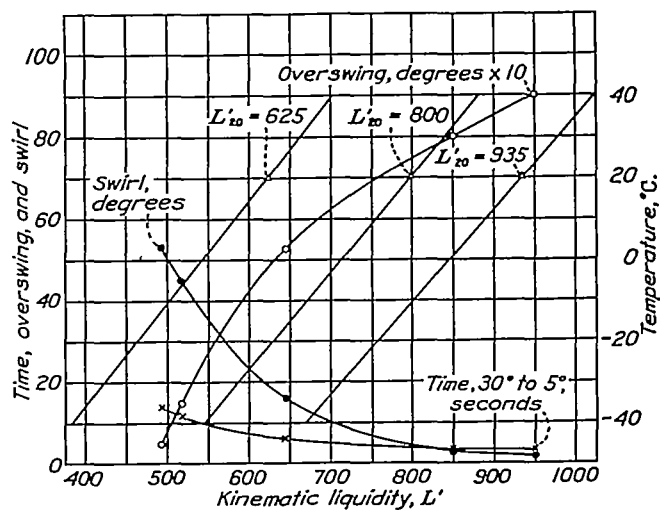


FIGURE 18.—Characteristics of KT65 aircraft compass.

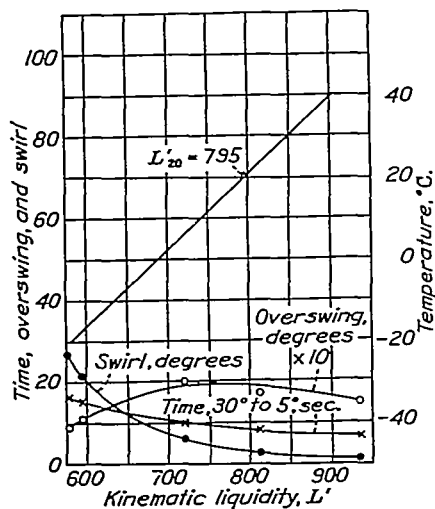
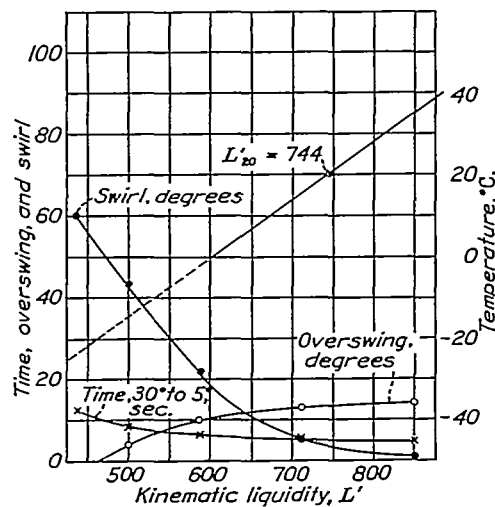
FIGURE 19.—Characteristics of British S₄O₂ aircraft compass.

FIGURE 20.—Characteristics of Morel Petit model 28 aircraft compass.

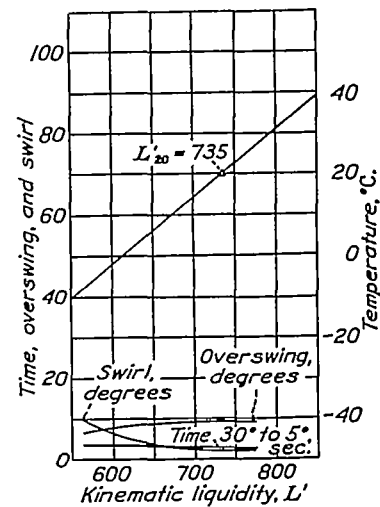


FIGURE 21.—Characteristics of Debris type 880 aircraft compass.

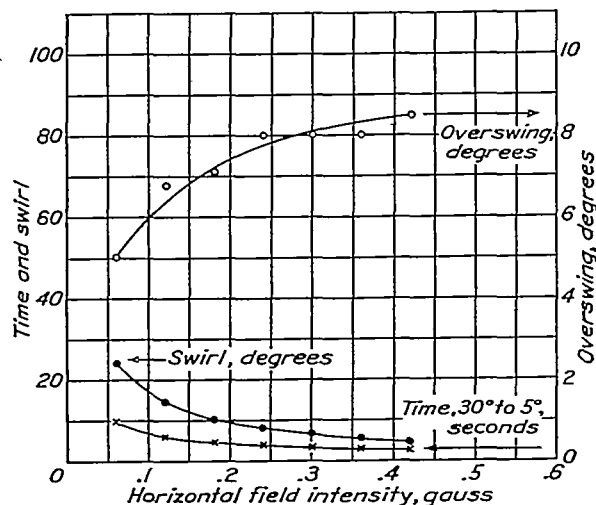


FIGURE 22.—Effect of magnetic field intensity on the characteristics of Navy VB aircraft compass at 20° C.

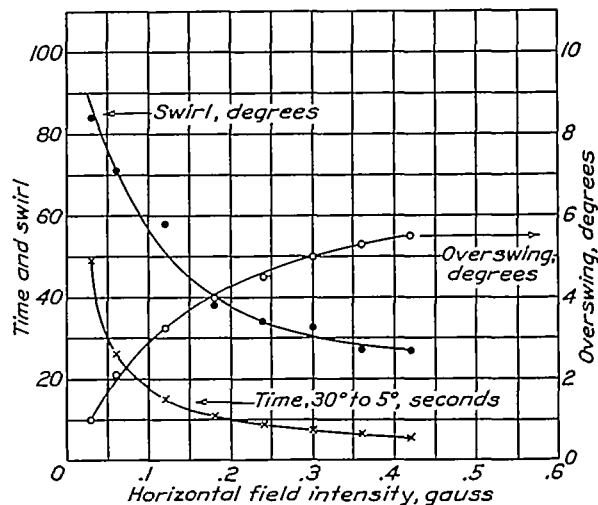


FIGURE 23.—Effect of magnetic field intensity on the characteristics of Navy VID aircraft compass at 20° C.

liquidities, the trade names and liquidities of which are:

	Kinematic liquidity L' at 20° C.
Superla clock oil.....	430
Album oil.....	470
Mineral spirits.....	800
Vacuum oil.....	935

A liquid of any intermediate liquidity may be obtained by mixing two of these mineral oils in the proportions given by Cragoe's equation for mixtures. Although the foregoing figures are representative, the liquidities of individual samples have been found to vary as much as ± 5 percent.

compass without arresting the card was employed. In the method a magnetometer is used to measure the change in the strength of the magnetic field caused by the presence of the compass.

The magnetometer is a short piece of magnetized cobalt steel suspended from a phosphor bronze strip at the center of a coil of known dimensions. The magnetometer is set up so that the axis of the coil is horizontal and parallel to the magnetic meridian. A torsion is applied to the suspension to cause the magnet to take a position perpendicular to the magnetic meridian and perpendicular to the axis of the coil, which will be called the "zero" position. When

TABLE I
AIRCRAFT COMPASS SPECIFICATIONS

	U. S. Navy compasses										U. S. Army		KT (U. S.)		Foreign		
	NSII	IV	V	VB	VI	VIB	VII	VIIIB	VIII	IX	B8	D4	58	65	A	B	C
Number of magnets.....	2	2	2	2	2	2	2	2	2	2	2	2	2	2	4		
Diameter of magnets, inches.....	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$			
Length of magnets, inches.....	2	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$			
Magnetic moment, cgs units.....	240	216	308	80	240	116	308	91	180	320	178	43	80	256	60	400	352
Card diameter, inches.....			$2\frac{1}{4}$	$2\frac{1}{4}$	4	4	3	3	$2\frac{1}{4}$	$3\frac{1}{4}$	$1\frac{3}{4}$			$3\frac{1}{4}$		$3\frac{1}{4}$	
Card weight in air, grams.....	7.4	7.2	8.4	5.4	7.8	6.4	8.4	5.8	12.5	17.2	8.2	2.9					29
Period in air, seconds.....				8.2		11.4		8.4									
Card weight in liquid, grams.....				4.3		5.1		4.7	1.0	1.5							3
Float.....	No	No	No	No	No	No	No	No	Yes	Yes	No	No	Yes	Yes	No	Yes	Yes
Damping liquid.....	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	O	P
Liquidity at 20° C.....	800	800	625	(625) (800)	625	(625) (800)	625	(625) (800)	800	935	935	670	625	800	795	740	735

A. Type S. O. 2 (large) compass (British).
B. Morel Petit model 28 compass (French).
C. Debrle type 860 compass (French).
M. Mineral oil.
N. 86 percent ethyl alcohol (by weight).
O. 31 percent ethyl alcohol (by weight).
P. 60 percent ethyl alcohol (by weight).

The Navy IV compass is filled with the liquid for which L' is 800. The Navy V, VI, and VII compasses were originally filled with a mixture of 47 percent mineral spirits and 53 percent album oil, the kinematic liquidity L' of the mixture being 625 at 20° C. (See fig. 3.) Navy V, VI, and VII compasses now in stock are being refilled with mineral spirits for which L' is 800 at 20° C. The VIII and IX compasses have damping liquids the kinematic liquidities of which are 800 and 935, respectively.

MAGNETIC FIELD STRENGTH

The standard horizontal magnetic field strength at which the time of swing, overswing, and swirl were measured, was 0.18 gauss, which is an average value for the United States. In order to give an idea of the variation in characteristics to be expected from variation in horizontal field strength, two representative compasses were tested at field strengths between 0.06 and 0.42 gauss. The characteristics of the two compasses for this range of field strength are shown in figures 22 and 23.

MAGNETIC MOMENT

A modification of the method described by Sanford (reference 9) for measuring the magnetic moment of a

making a measurement, the compass is brought to a definite position on the axis of the coil, causing a deflection of the magnetometer. The electric current in the coil necessary to restore the deflection to zero is determined. From this current, the dimensions of the coil, and the distance of the compass from the magnetometer, the moment of the magnetic system of the compass is calculated. Since the change in field strength due to the compass magnets is a very small percentage of the total field strength, it is essential that this measurement be made at a location where the field will be undisturbed.

The magnetic moment for each type of compass, as derived by this procedure, is given in table I.

FLIGHT TESTS

In Navy practice there are two distinct uses of a compass. It may be used as a steering indicator, the pilot steering the airplane according to its indications. It may be used as a checking compass to check occasionally the course of an airplane that is being steered on a straight course according to the indications of a directional gyro.

In an attempt to compare compasses of different characteristics in flight, a series of tests were made on compasses in pairs. As representative of the results

obtained in this series of tests a part of the comparative tests on Navy IV and VIB compasses are shown in figures 24 and 25. In the steering tests the pilot steered by the compass and an observer took about 30 readings per minute on a directional gyro. In the checking tests, the pilot steered by the directional gyro and an observer took readings on the compass.

Each compass was tested on north and on south courses, both as a steering compass and as a checking compass. As a steering compass, the performance is worse on a north course because of the northerly turning error. When an airplane turns from a north course, the centrifugal acceleration of the turn causes the compass card to tilt out of the horizontal position into such a position that the earth's vertical magnetic field will cause the card to deflect in the direction in which the airplane has turned. It is easily possible for the card of any unstabilized compass to turn faster than the airplane, indicating to the pilot a turn in the

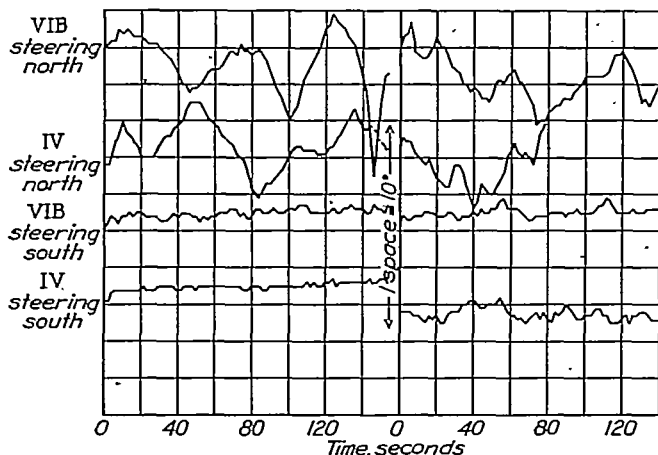


FIGURE 24.—Flight tests of steering compasses.

opposite direction. At the magnetic equator there is no northerly turning error and south of the magnetic equator the southerly turning error becomes troublesome.

The results of these tests are shown in table II. The values given are the average deviations of the readings from a straight line faired between the plotted points. Comparisons should be made only between two compasses of the same pair, because another pair may have been tested at another time when the air may have been rougher or smoother. It is assumed that the air conditions remained constant during the time required to test one pair.

Although definite conclusions should not be drawn from the results of the few tests presented here, there is a strong indication that the short-period compass is better for steering and the long-period compass with a low overswing is better for checking. It is the belief of the authors that the yawing oscillations of an airplane being steered according to the indications of a

compass may vary greatly with different pilots. Practically all of the flight data of this report were obtained by the junior author and by Ira E. Hobbs, lieutenant, United States Navy. It is very desirable that flight tests be continued with other compasses, other pilots, and automatic pilots. Probably also, photographic methods of recording the instrument readings should be utilized.

The results of these flight tests can be explained on the basis of the difference in the periods of the compass and the yawing of the airplane. An airplane steering on a north course, according to the indications of a compass, oscillates with a period longer than the period of the compass, while an airplane steered according to the indications of the relatively stable directional gyro oscillates with a period shorter than the periods of the compasses in this group. The curves of figure 24 show clearly that the period of the yawing oscillation of the airplane steered according to the indication of a compass on a north course is much longer than the period of the compass by which it is being steered (approx-

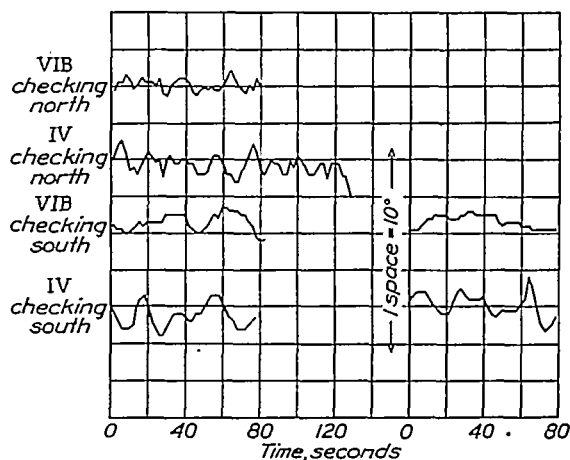


FIGURE 25.—Flight tests of checking compasses.

imate periods, airplane, 60 seconds; compass IV, 19 seconds; compass VIB, 30 seconds).

TABLE II
RESULTS OF FLIGHT TESTS ON COMPASSES

Compass	Time, 30° to 5°	Overswing	Swirl	Steering error		Checking error	
				North	South	North	South
VI-----	Seconds	Degrees	Degrees	Degrees	Degrees	Degrees	Degrees
V-----	11.6	3.5	29	4.1	-----	1.5	-----
	14.0	1.5	45	7.0	-----	1.3	-----
IV-----	4.8	6.2	10	3.0	1.1	3.7	-----
V-----	14.0	1.5	45	6.8	1.1	1.7	-----
IV-----	5.0	6.0	11	4.6	1.1	2.0	2.5
VIB-----	8.0	6.5	14	5.3	1.2	1.4	1.7
VIB-----	8.0	6.5	14	5.3	.9	1.1	3.1
VIB-----	12.0	3.5	31	6.8	1.3	1.2	1.2
IV-----	3.2	8.5	8.2	2.8	2.1	1.8	3.3
S. O. 2-----	9.2	2.0	5.0	3.1	2.4	2.1	6.8

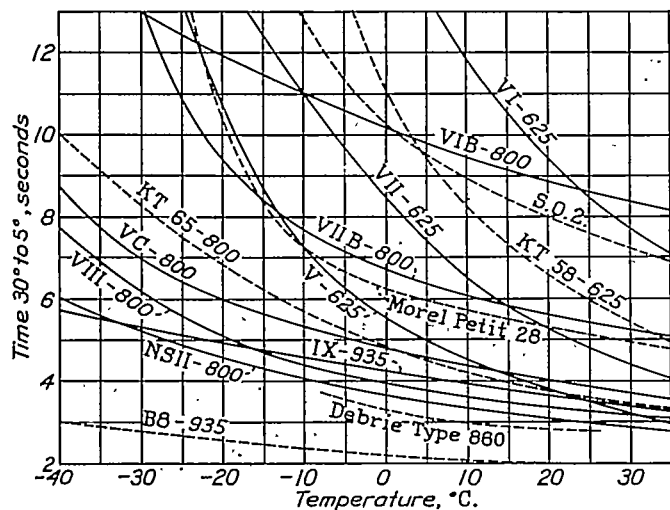


FIGURE 26.—Summary chart, time of swing against temperature.

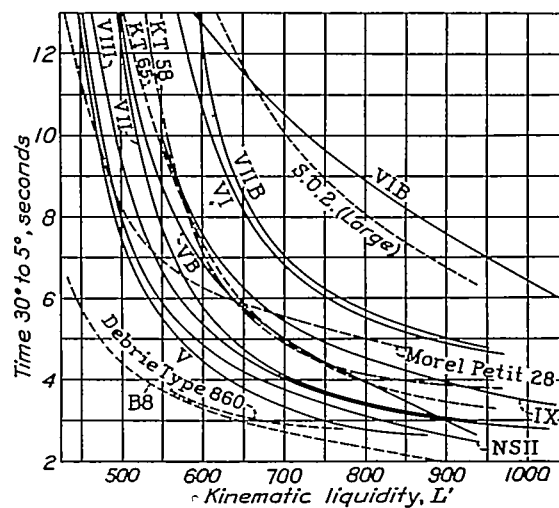


FIGURE 29.—Summary chart, time of swing against liquidity.

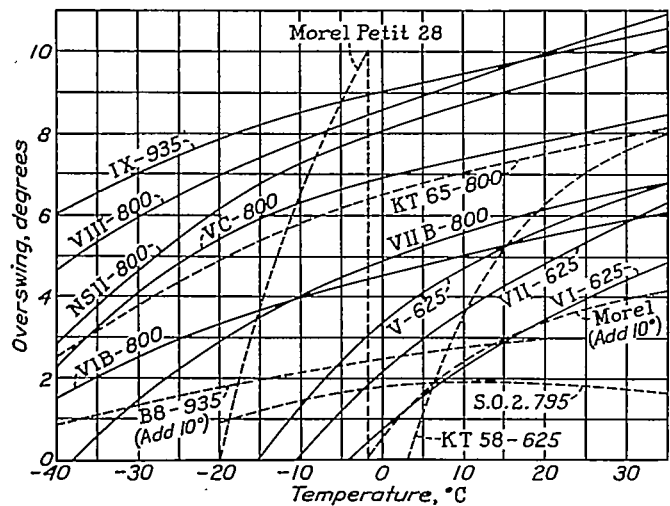


FIGURE 27.—Summary chart, overswing against temperature

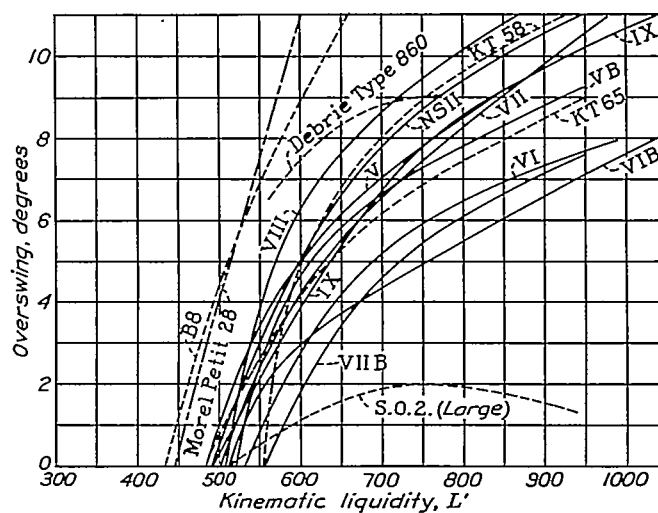


FIGURE 30.—Summary chart, overswing against liquidity.

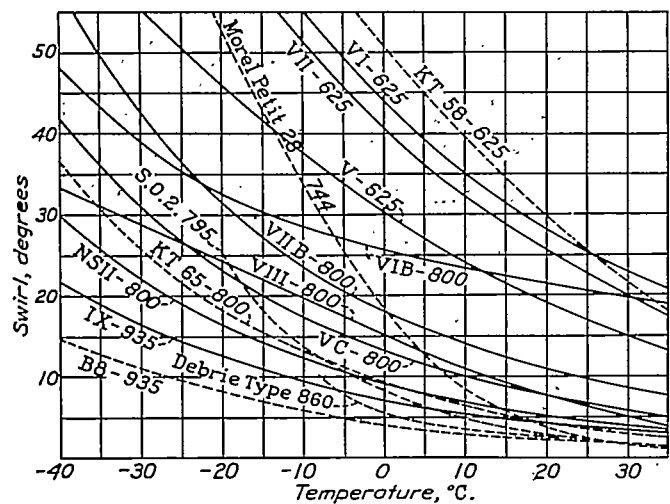


FIGURE 28.—Summary chart, swirl against temperature.

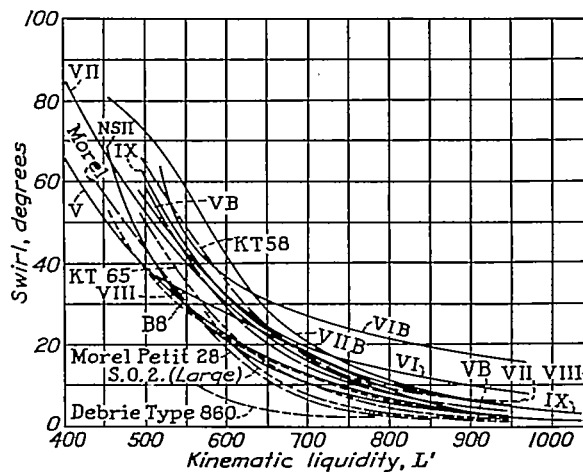


FIGURE 31.—Summary chart, swirl against liquidity.

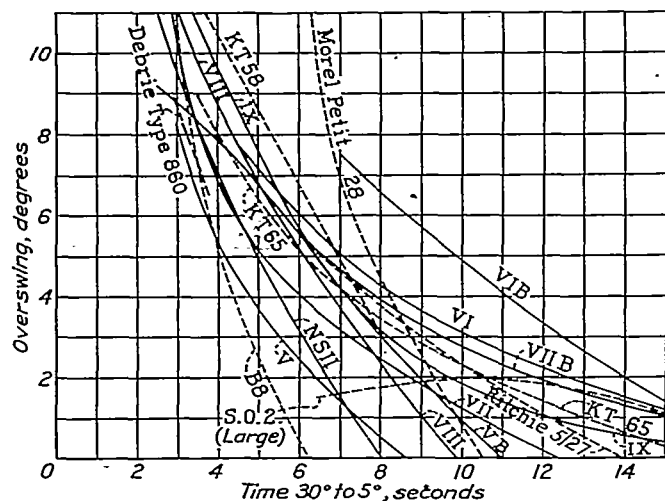


FIGURE 32.—Summary chart, overswing against time of swing.

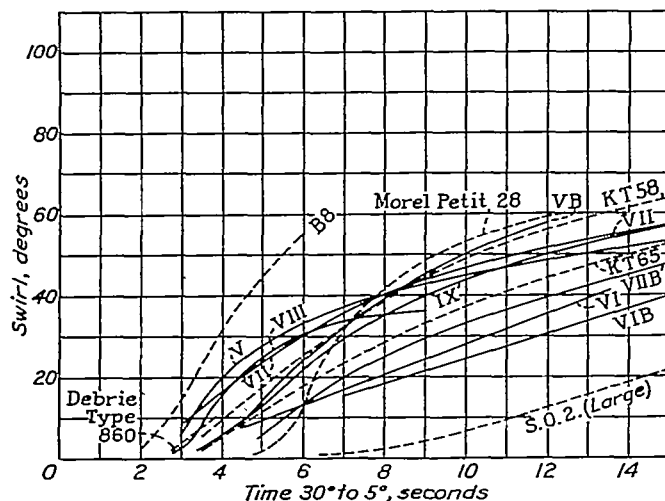


FIGURE 33.—Summary chart, swirl against time of swing

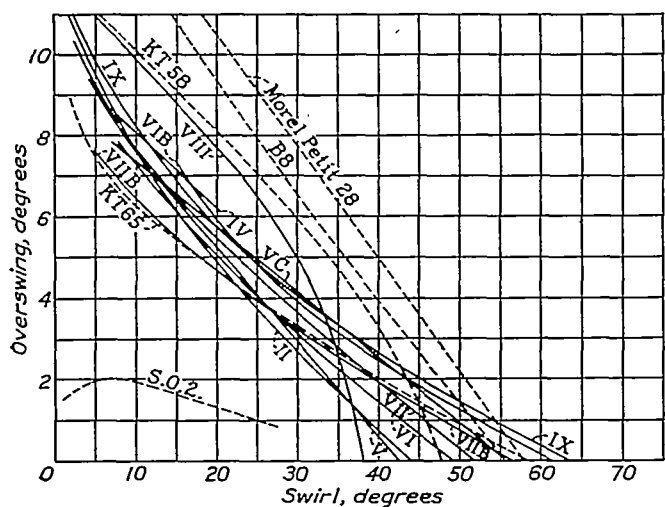


FIGURE 34.—Summary chart, overswing against swirl.

DISCUSSION

The curves for time of swing, overswing, and swirl shown in figures 5 to 21, for the individual compasses are summarized from various points of view in figures 26 to 34. Figures 26, 27, and 28 show the variations of time of swing, overswing, and swirl with temperature. Figures 29, 30, and 31 show the variations of the same quantities with liquidity. Figures 32, 33, and 34 show the variations of time of swing, overswing, and swirl, one relative to the other. The variations in the characteristics were obtained by varying the liquidity of the damping liquid.

It is very probable that low time of swing, low overswing, and low swirl are desirable characteristics for good performance in flight. These requirements are not simple to meet because low overswing and low swirl are conflicting requirements as may be seen in figure 34. Low overswing may be obtained by the use of weak magnets and a viscous damping liquid but their use causes a long time of swing and a high swirl. A low swirl and a short time of swing may be obtained by the use of strong magnets and a thin damping liquid of low viscosity but a high overswing is thereby produced.

Opposite extremes of performance are shown in figures 32, 33, and 34 by the British S. O. 2. compass and the French Morel Petit model 28 compass. The low overswing and low swirl of the S. O. 2. compass are obtained by the use of an extremely light and relatively fragile magnetic card. It has been the experience of the authors that this instrument is too fragile for service use. The magnetic moment is so low that the pivot must be in perfect condition if excessive friction is to be avoided. On the other extreme, the Morel compass has a very heavy floated card and a high magnetic moment. Practically all American compasses have characteristics between the British and French extremes. Of the American compasses in this report, only the Navy VIII and IX and the two KT compasses have cards with floats.

The curves of figures 32, 33, and 34 are an aid in the selection of compasses for flight tests. As an example of the use of these curves it will be seen that by a suitable choice of damping liquids the Army B8 and Navy VIB compasses may be given any of the following characteristics at any selected temperature of the compass.

The chief reason for the difference in characteristics of the B8 and the VIB is the difference in size of the card. The B8 card has a diameter of $1\frac{1}{4}$ inches and the VIB card has a diameter of 4 inches. The clearance

between the bowl and the card is approximately the same for both compasses.

TABLE III

Compass	Time 30° to 5°	Over- swing	Swirl
	<i>Seconds</i>	<i>Degrees</i>	<i>Degrees</i>
Bs.-----	6.0	0.4	55
VIB.-----	6.0	8.5	12
Bs.-----	4.0	5.0	36
VIB.-----	9.8	5.0	24
Bs.-----	3.9	6.0	30
VIB.-----	11.8	3.9	30

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